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Ultrafast, ultra-broadband superlattice detector for THz radiation

E.Schomburg, F.Klappenberger, M.Krätschmer, A.A.Ignatov, K.F.Renk, and W.Wegscheider

Abstract **– We report on a novel detector for THz radiation. It consists of a GaAs/AlAs superlattice mesa device mounted in a corner cube antenna system. The detector shows a current-voltage characteristic with a negative differential conductance. Under the influence of THz radiation, the dc current through the superlattice mesa is reduced; this is caused by a THz field-induced modulation of Bloch oscillating miniband electrons in the superlattice. A fast detector response (several tenth of picoseconds, limited by the electronics) and a high responsivity is demonstrated in a frequency range 0.7-7 THz.**

I. Introduction

Semiconductor superlattices, as proposed by Esaki and Tsu [1], show non-linear electrical transport properties due to their unique bandstructure consisting of minibands along the superlattice axis. It has been found that a doped superlattice showed a negative differential conductance [2] and that THz radiation applied to a superlattice by an antenna resulted in a reduction of the direct current [3, 4]. In this contribution, we report on the use of a GaAs/AlAs superlattice mesa device mounted in a corner cube antenna system as THz detector and discuss results of temporal resolution, responsivity and dynamical range. All experiments were performed with the detector at room temperature.

II. The Detector

The main element of the detector is a superlattice device fabricated from a n-type doped GaAs/AlAs superlattice (doping level $1 \cdot 10^{17}\,cm^{-3}$), which was grown by molecular beam epitaxy on a n^+ GaAs substrate. For our study, we used different superlattices, which typically consisted of 100 periods; a period contained a GaAs and a AlAs layer. The thickness of these layers was chosen that a miniband width in the order of 100 meV was obtained. The device (area: 200x200 μm^2) consisted of superlattice mesas (diameter about 4 μm) in a honeycomb-like arrangement on the GaAs substrate. Each mesa was covered by an ohmic contact. An additional ohmic contact was made on the n^+ GaAs substrate.

The superlattice device was mounted in a corner cube antenna system (Fig.1). A single superlattice mesa was contacted with a gold wire connecting the mesa to ground for the direct current. The wire acted as a long wire L-antenna for the THz radiation and was placed in a 90-degree corner cube reflector. A second contact to the superlattice mesa was established by connecting the substrate contact to the inner wire of a coaxial line. The coaxial line was used to couple the detector response to an oscilloscope (input impedance 50 Ω) and to apply a constant voltage to the superlattice. Outside the detector, detector response and bias voltage were separated by a bias tee. In order to test the detector, we used radiation from the FELIX free electron laser. For a lower frequency (700 GHz), a backward-wave oscillator was used.

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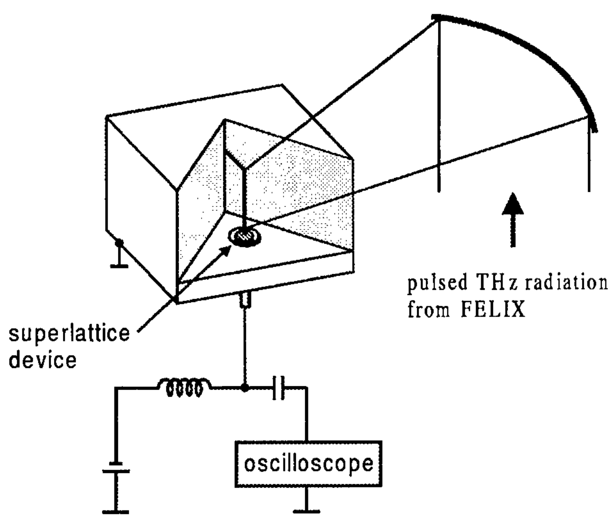

Fig. 1: Experimental set-up.

III. Results

The current-voltage characteristic (Fig.2) of a superlattice mesa showed ohmic behaviour for small voltages and had a negative differential conductance for higher voltages. The current maximum corresponded to a current density of about 100 kA/cm^2.

The coupling of THz radiation to a superlattice mesa leads to a reduction of the current. This current reduction is the basis of the detector response monitored by the oscilloscope. As example, the signal for a radiation pulse at 7 THz and a duration of 6 ps is given in Fig.3. The detector signal has a duration (halfwidth) of about 30 ps; the temporal resolution was limited by the electronics, mainly the bandwidth of the oscilloscope and the jitter in the trigger.

Recently, it was shown [5] using a differential electronic gating technique developed by a group at the Delft

University of Technology (N.Hovenier et al.) that our superlattice detector can temporal resolve 10-ps THz pulses (the measurements were performed at frequency of about 2 THz) from the FELIX free electron laser.

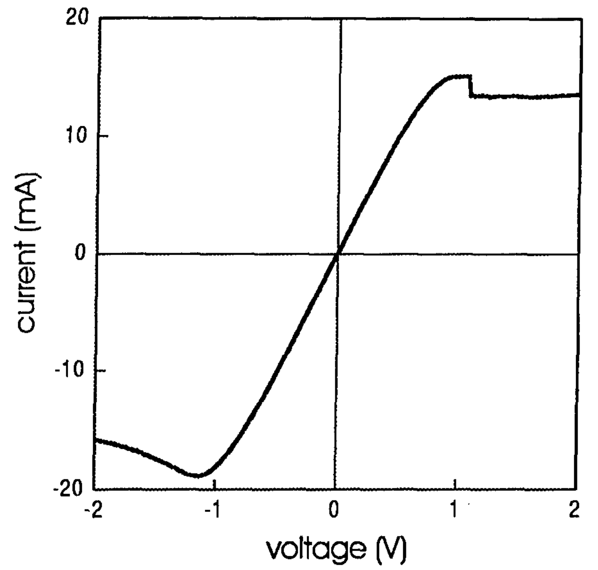

Fig. 2: Current-voltage characteristic of a superlattice mesa.

The dynamical range of the superlattice detector, i.e. the range in which the detector signal is proportional to the radiation power, is several orders of magnitude. For a superlattice (miniband width 105 meV) at 2.5 THz the smallest power registrated from a cw laser was below 100 μW, while the largest power detected from a FELIX pulse was about 5 W before the detector starts to saturate.

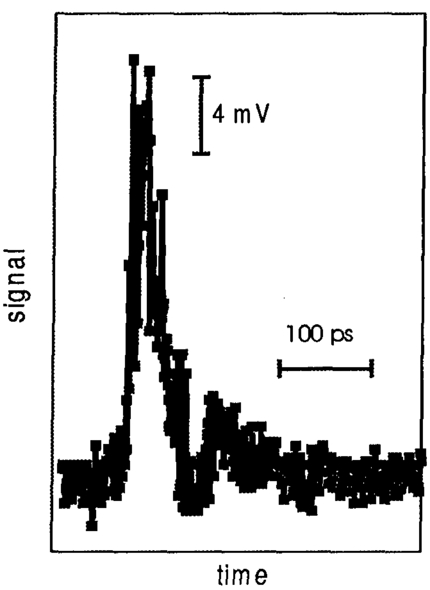

Fig. 3: Signal of a superlattice detector in response to a FELIX pulse (duration: 6 ps; energy: 2 nJ) at 7 THz.

An overview of the voltage responsivity (which is the signal voltage corresponding to the current reduction at a 50 Ω load impedance) of superlattice detectors, with miniband widths of the order of 100 meV, is given in Fig.4. The superlattice mesas were biased near the current maxima, where the highest responsivity was found. The responsivity was proportional to f^{-4}, where f is the radiation frequency. For comparison, Schottky diodes [6] mounted in a similar corner cube antenna system has a much higher responsivity (more than an order of magnitude at 700 GHz and about three orders of magnitude at 2.5 THz). However, Schottky diodes can be destroyed by intense THz radiation pulses. The superlattice detector was irradiated with THz-laser pulses (duration 5...10 ps) of the order of kilowatts without being destroyed. In comparison to the interband detector [7] and the photon drag detector [8], which have a similar robustness against high power levels and comparable time resolution, the superlattice detector has a responsivity being several orders of magnitude higher.

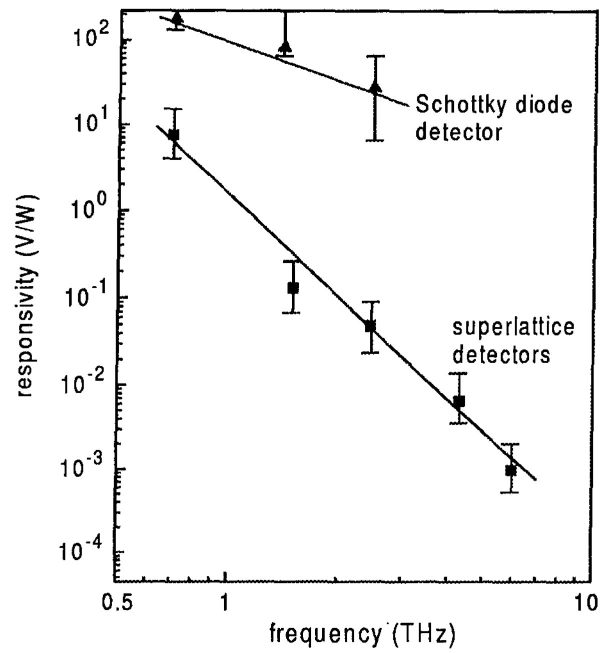

Fig. 4: Responsivity of superlattice detectors (squares) and Schottky diode detectors (data taken from [6]).

IV. The Physics of the Detector

The current along the superlattice is mainly carried by electrons in the energetically lowest miniband. The negative differential conductance indicates that miniband electrons perform Bloch oscillations. According to the Esaki-Tsu model [1] of miniband transport, the negative differential conductance occurred for fields larger than a critical field $E_c = \hbar/(ea\tau)$, where e is the elementary charge, $\hbar$ Planck's constant, a the period of the superlattice and τ the intraminiband relaxation time. An analysis of current-voltage characteristics of different superlattices with wide minibands indicated a value of the order of 10^{-13} s for the intraminiband relaxation time. Thus, for the THz frequency range, the condition of a dynamical interaction ($2\pi f\tau \geq 1$) of the miniband electrons with the THz field is fulfilled. An earlier study [4] showed that the response of a superlattice to THz radiation corresponded to classical rectification for $2\pi f\tau < 1$ and to dynamical interaction for $2\pi f\tau \geq 1$. In the case of dynamical interaction the miniband electrons perform frequency-modulated Bloch oscillations; the modulation frequency is equal to the frequency of the

THz radiation and the modulation degree is determined by the amplitude of the THz field inside the superlattice. The modulation leads to a reduction of the spatial amplitude of the Bloch oscillations corresponding to a dynamical localisation of the miniband electrons. The localisation causes the reduction of current and, therefore, leads to the detector response. Intrinsically, the characteristic response time of a superlattice to a change in the THz field is governed by the intraminiband relaxation time.

An analysis of the responsivity of a superlattice detector [9] indicated a decrease of the responsivity with the fourth power of the frequency, which is in good agreement with our experimental results. Furthermore, the analysis showed that the responsivity is proportional to the maximum current density of the superlattice and is inversely proportional to the cross-section of the superlattice mesa. Therefore, an increase of the doping level in the superlattice and a reduction of the mesa area should lead to an increase of responsivity.

V. CONCLUSION

A new room temperature THz detector was described. The detector has an intrinsic response time of the order of 10^{-13} s, a large range of response (from smaller 0.7 THz to 7 THz) and a large dynamical range. The detector is robust against intense radiation pulses. Our detector is most suitable for the characterisation of intense ultrashort THz radiation pulses.

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